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THE VISCOELASTIC BEHAVIOR OF A COMPOSITE IN A THERMAL ENVIRONMENT

by

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ABSTRACT

A proposed method for the accelerated predictions of modulus and life times for time dependent polymer matrix composite laminates is presented. The method, based on the time-temperature superposition principle and lamination theory, is described in detail. Unidirectional reciprocal of compliance master curves and the shift functions needed are presented and discussed. Master curves for arbitrarily oriented unidirectional laminates are predicted and compared with experimental results obtained from master curves generated from 15-minute tests and with 25-hour tests. Good agreement is shown.

Predicted 30° and 60° unidirectional strength master curves are presented and compared to results of creep-rupture tests. Reasonable agreement is demonstrated. In addition, creep-rupture results for a $[90°/\pm 60°/90°]_{2s}$ laminate are presented.

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INTRODUCTION

The merits of composite materials for potential use in structural design are well established. Their high strength to weight ratio make them attractive in aerospace and automotive applications where improved fuel economy by weight reduction is desirable. Unfortunately, a number of factors have inhibited the ready acceptance of such materials. First, costs are high compared to conventional materials. With increased usage, however, costs are likely to become increasingly competitive in the future. Another, perhaps more serious limitation, is the current lack of understanding of the mechanical behavior of polymer based laminates under long term environmental exposure.

It is well known that the epoxy resins which are now often used as the polymer matrix component exhibit viscoelastic or time effects which are significantly affected by exposure to both temperature and humidity. Epoxies soften as temperatures are increased with resulting loss of both moduli and strength.[1-4] In addition, they absorb moisture and swell giving rise to residual stresses.[5-8]

Polymer based composite laminates will be similarly time dependent and affected by moisture and temperature under certain circumstances. Fiber dominated composites are not likely to suffer large reductions of either moduli or strength in the fiber direction. In other directions, time, temperature, and moisture dependent losses of both strength and modulus are likely.

Because of the effects of environment, there is concern that time dependent properties such as creep, relaxation, creep ruptures, etc., may

be important long-term design considerations for the temperature and moisture levels anticipated in current structural applications. It would be desirable to be able to measure the environmental effects with short-term laboratory tests rather than perform long-term prototype studies. In addition, it would be desirable to be able to predict these effects with analytical techniques for either short- or long-term situations. As a result, it is clear that there is a need for accelerated characterization techniques for laminates similar to those used for other structural materials.

For metals and polymers a variety of techniques are available such as linear elastic stress analysis, empirical extrapolative equations such as the Larson-Miller parameter method, and the time-temperature superposition principle. Several procedures have been proposed for the purpose of making such lifetime or viscoelastic predictions of composite materials. Some of these are the "wear out model" proposed by Halpin, Jernia, and Johnson,[9] a non-linear viscoelastic technique proposed by Lou and Schapery,[10] and a combined viscoelastic-lamination theory model proposed by De Runtz and Crossman.[11] The former[9] is a statistically based method for the prediction of fatigue lifetimes and the latter[10-11] are methods to predict environmental degradations of moduli or compliances.

The purpose of the work reported herein was to develop an accelerated characterization method by which design information or predictions of long time moduli and strength could be made from short-term tests on graphite/epoxy laminates. In general, the procedure is based upon the time-temperature superposition principle and the widely used lamination theory for composite materials.

ACCELERATED CHARACTERIZATION AND FAILURE PREDICTION

The procedures for accelerated characterization and life time predictions are outlined in Fig. 1. Using these proposed procedures a designer can systematically incorporate predictions of long term viscoelastic failures in the initial design process. That is, by use of the method shown in Fig. 1, delayed failures during the life time of a structural component can be avoided. Thus, the ideas of Fig. 1 are for an arbitrary polymer based composite laminate. In the discussion to follow, the particular laminate being studied is a 350°F cured graphite/epoxy system, T300/934.

The various experimental and analytical procedures undertaken to verify the proposed methodology given in Fig. 1 are outlined below. The letters of the items below agree with those identifying each task in Fig. 1.

ITEM A: Tests to Determine Lamina Modulus Master Curves

As previously mentioned, the proposed accelerated characterization method is based upon the time-temperature superposition principle (TTSP) for polymeric materials. The validity of the TTSP for the T300/934 graphite/epoxy system has been established.[12]

Figure 2 shows the results of short term (15 min.) creep tests on a $[90°]_{8s}$ specimen at various temperatures. The ordinate of this figure is reciprocal of reduced compliance, which is calculated using[12] $S_{22} = \frac{T}{T_o} \frac{\epsilon(t)}{\sigma}$ where T = temperature (°R), T_o = reference temperature (taken to be the glass transition temperature of 453°R), $\epsilon(t)$ is the time dependent axial strain, and σ is the applied axial stress. Figure 2 also shows a portion of the master curve, while Fig. 3 shows the complete

master curve. The master curve is obtained by horizontally shifting the short-time data until a smooth curve is obtained. The amount of horizontal shift at each temperature is the shift factor, a_T.

Testing was performed at other fiber angles than 90°, and master curves similar to Fig. 3 were constructed.[13] The need for such master curves will be subsequently discussed. It is assumed that reciprocal of compliance, such as shown in Figs. 2 and 3, is equal to modulus. Such an assumption appears to be justified.[14]

ITEM B: Established Shift Function Relationship

Graphical shifting of short-time (15 min.) data to determine shift factors as a function of temperature for various fiber angles gave the results shown in Fig. 4. Examination of this figure reveals that the shift function is relatively insensitive to fiber orientation. This result is important when calculating lamina modulus for an arbitrary fiber angle using anisotropic transformation equations.

ITEM C: Predicted Lamina Modulus for Arbitrary Fiber Angle

The viscoelastic compliance of an arbitrary ply in a general laminate (which is assumed to be the same as a unidirectional laminate of the same fiber orientation) for any time t may be found using the orthotropic transformation equation

$$S_{xx}(t) = m^4S_{11} + 2m^2n^2S_{12} + n^4S_{22}(t) + m^2n^2S_{66}(t) \tag{1}$$

where $S_{xx}(t)$ is the time dependent compliance in the load direction for a specimen with the fibers oriented θ degrees from the loading axis, $m = \cos\theta$, $n = \sin\theta$, and S_{11}, S_{12}, S_{22}, and S_{66} are components of the

principal compliance matrix.[15] A previous study[12] found S_{11} and S_{12} to be independent of time for our graphite/epoxy material. The time dependent compliances $S_{22}(t)$ and $S_{66}(t)$ are found from creep tests of specimens with fiber orientations of 90° and 10°, respectively.[12]

Figure 5 shows a comparison between the predicted master curve using equation (1) and those obtained using the time-temperature superposition principle with short-term (15 min.) tests for a specimen whose fibers are at an angle of 30° with the load axis. Similar comparisons were made for other fiber orientations and in all cases agreement was moderate to good.[13]

To further validate the predictive ability of equation (1) and the applicability of the time-temperature superposition principle, medium-term, 25-hour creep tests were also run for a number of fiber angles. Figures 3 and 5 show the results for 90° and 30°, respectively. Favorable comparisons exist between the results using the time-temperature superposition principle (15-min. tests), the transformation equation (1), and the medium-term, 25-hour data. Similar results were obtained for other orientations.[13]

ITEM D: Lamina Modulus Master Curve for Arbitrary Temperature and Fiber Angle

Given the information in A, B and C, a master curve for the modulus of a lamina or ply of arbitrary fiber orientation can be found for an arbitrary reference temperature. This is needed input for any computational scheme to predict laminate failure, as shown in Item G.

For example, Fig. 6 shows master curves, at three temperatures, for a laminate with a fiber orientation of 30°. These curves were generated

using the 180°C master curve (Fig. 5), the transformation equation (1), and the shift function-temperature relationship shown in Fig. 4. Similar results may be found for other fiber orientations.

ITEM E: Predicted Lamina Strength for Arbitrary Fiber Angle

The strengths of laminates of various fiber orientations were obtained by ramp loading the specimens to failure. Figure 7 shows the results for two temperatures. The theoretical predictions were made using the Puppo-Evensen failure criterion[16] given by

$$\frac{1}{\sigma_x^2} = \left[\frac{\cos^2\theta}{X_{11}}\right]^2 - \gamma\left[\frac{X_{11}}{X_{22}}\right]\left[\frac{\cos^2\theta}{X_{11}}\right]\left[\frac{\sin^2\theta}{X_{22}}\right] + \gamma\left[\frac{\sin^2\theta}{X_{22}}\right]^2 + \left[\frac{\cos\theta\sin\theta}{X_{66}}\right]^2 \quad (2)$$

$$\frac{1}{\sigma_x^2} = \gamma\left[\frac{\cos^2\theta}{X_{11}}\right]^2 - \gamma\left[\frac{X_{22}}{X_{11}}\right]\left[\frac{\cos^2\theta}{X_{11}}\right]\left[\frac{\sin^2\theta}{X_{22}}\right] + \left[\frac{\sin^2\theta}{X_{22}}\right]^2 + \left[\frac{\cos\theta\sin\theta}{X_{66}}\right]^2 \quad (3)$$

where $\gamma = \left[\frac{3X_{66}^2}{X_{11}X_{22}}\right]^n$

and σ_x = applied uniaxial stress, X_{11} is the strength of a 0° specimen, X_{22} is the strength of a 90° specimen, X_{66} is the strength of a 10° specimen, and n is a material parameter. Using a value of n = 1, it was found that equation (2) gave good correlations for $\theta < 45°$, and equation (3) gave good correlations for $\theta > 45°$.

ITEM F: Lamina Strength Master Curve for Arbitrary Temperature and Fiber Angle

Due to the length of time needed to perform enough testing to experimentally determine strength master curves for an arbitrary temperature and for arbitrary fiber angles, it was assumed that strength master curves would have the same shape with the same shift function as the corresponding

compliance master curve. As a result strength master curves were determined by using the corresponding ramp loaded strengths[17] and the known shape of the compliance master curves and shift function from Items A, B and D. Portions of strength master curves so generated are shown in Figs. 8 and 9 for fiber orientations of 30° and 60°, respectively. Also shown in Figs. 8 and 9 are the results of creep rupture tests.

Deviations between predicted and measured creep rupture stresses are less than 25% over the range of data. However, predictions on creep to rupture times differ with measurements from one to three orders of magnitude. Such large errors appear to be inherent in a creep rupture process.[18]

ITEM G: Incremental Lamination Theory Based on Master Curves to Predict Long-Term Laminate Response

Using the well known time independent lamination theory,[19] an incremental lamination theory could be developed which would predict the moduli and strength of arbitrary laminates based upon the lamina modulus and strength master curves developed in Items D and F. Efforts are underway to develop the incremental lamination theory. The results will be presented at a later date.

ITEM H: Long-Term Laminate Tests to Verify Long-Term Predictions

The results of creep rupture tests for a $[90°/\pm 60°/90°]_{2s}$ laminate are shown in Fig. 10. There is a large amount of scatter in the data. As previously stated, such scatter appears to be inherent in a creep rupture process. Comparison between predicted results (Item G) and experimental results are not available at this time.

SUMMARY AND CONCLUSIONS

The purpose of the work reported herein was to develop an accelerated characterization method by which long-term predictions of time dependent moduli and strength could be made on the basis of short-time laboratory tests. The method was based on the time-temperature superposition principle and lamination theory.

Several key assumptions were made regarding the accelerated characterization method shown in Fig. 1. For example, the orthotropic transformation equation for composites was assumed to be valid for time dependent moduli (Item C). Figure 5 shows that this assumption is reasonably correct.

The TTSP was assumed to be valid for both moduli and strengths, and strength master curves were assumed to have the same shape as modulus master curves. These assumptions led to predictions of lamina strength which were in error less than 25% from measured strengths, as shown in Figs. 8 and 9.

It was also assumed that classical lamination theory, in incremental form, was valid. The validity of this assumption awaits development of an incremental lamination theory, and comparison with the experimental results shown in Fig. 10.

It should be noted that all data generated herein was for small stress and strain levels such that linear viscoelastic concepts be applicable. When failures such as creep ruptures occur, stresses and strains at the point of failure are high, and nonlinear processes are likely to be involved. Thus, it is reasonable to assume that master

curves and shift functions are also likely to be stress dependent. Without further experimental evidence, it is likely that nonlinear processes may result in large variations between predictions and the experimental results shown in Fig. 10.

Finally, a time independent failure law of Puppo and Evensen was assumed to be valid by simply including time dependent data in determining the necessary constants. Further work is needed to validate this assumption.

Efforts are underway to investigation the nonlinear effects, to find a time dependent failure law, and to incorporate these into the lamination theory process for moduli and strength predictions.

ACKNOWLEDGMENTS

The financial support provided for this work by NASA Grant NSG 2038 from the Materials and Physical Sciences Branch of Ames Research Center is gratefully acknowledged. Further, sincere apprcciation is extended to H. G. Nelson of NASA-Ames for his encouragement and many helpful suggestions.

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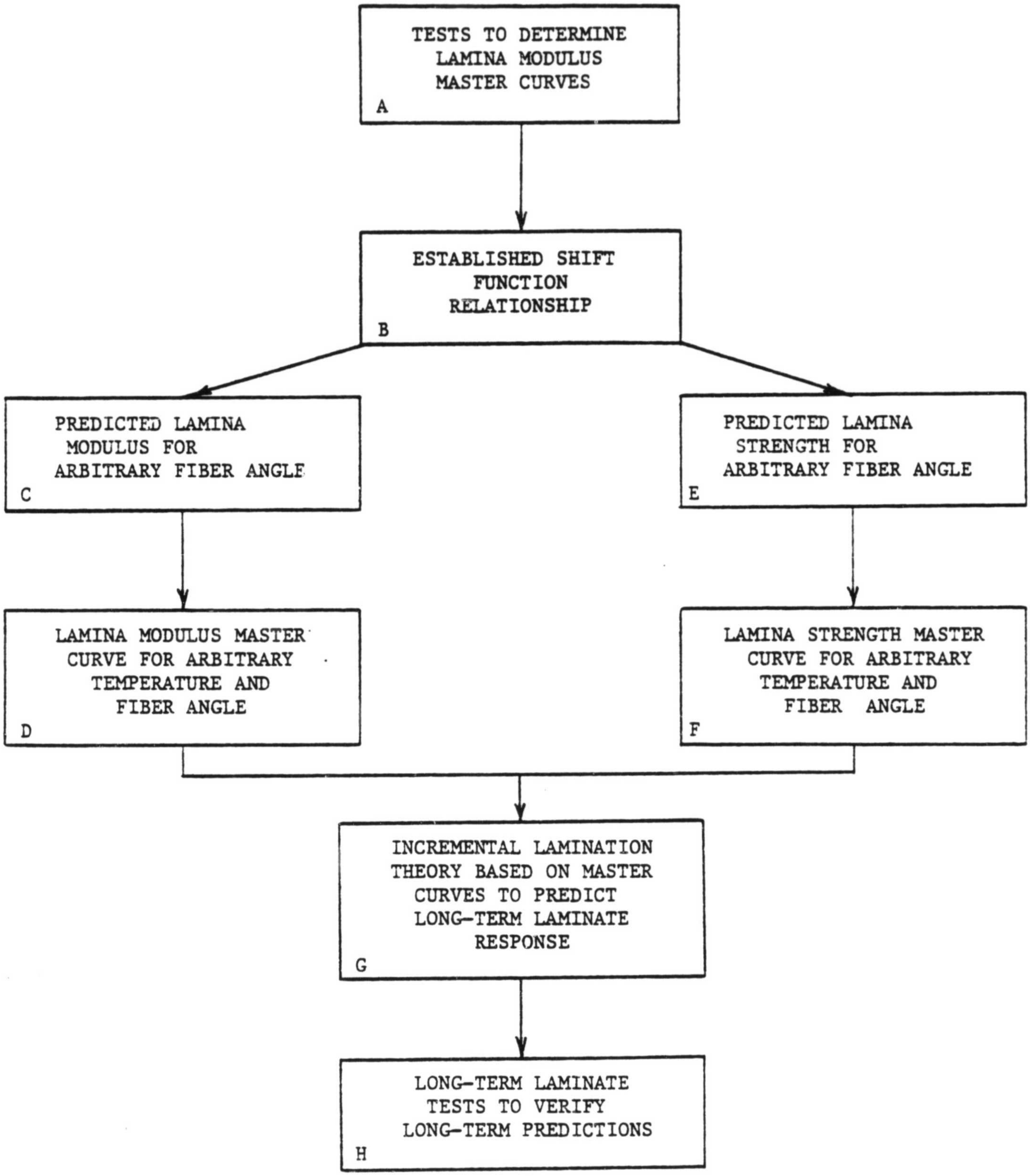

Fig. 1. Flow Chart of the Proposed Procedures for Laminate Accelerated Characterization and Failure Prediction

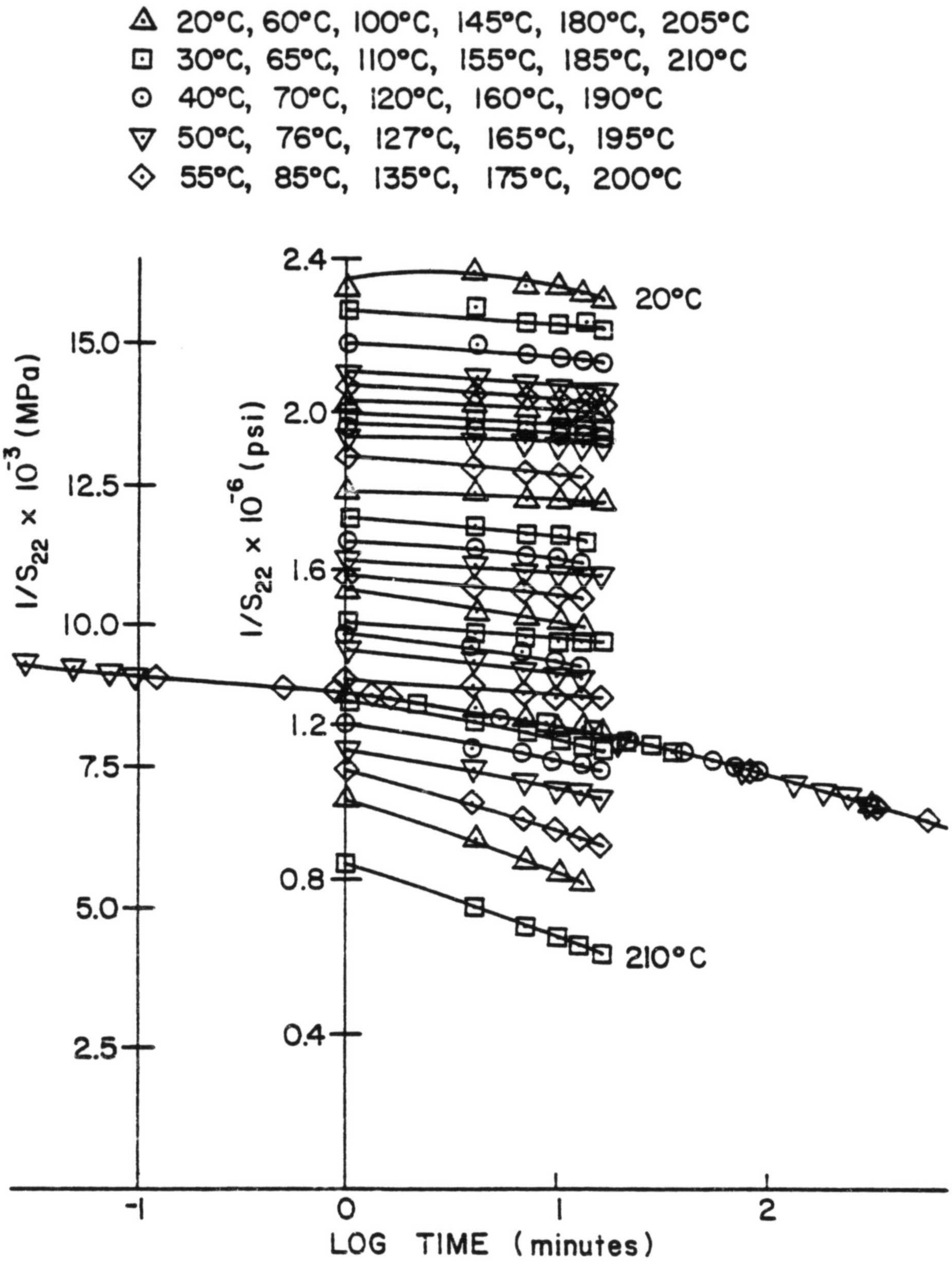

Fig. 2. Reduced Reciprocal of Compliance, $1/S_{22}$, and Portion of 180°C Master Curve for $[90°]_{8s}$ T300/934 Graphite/Epoxy Laminate

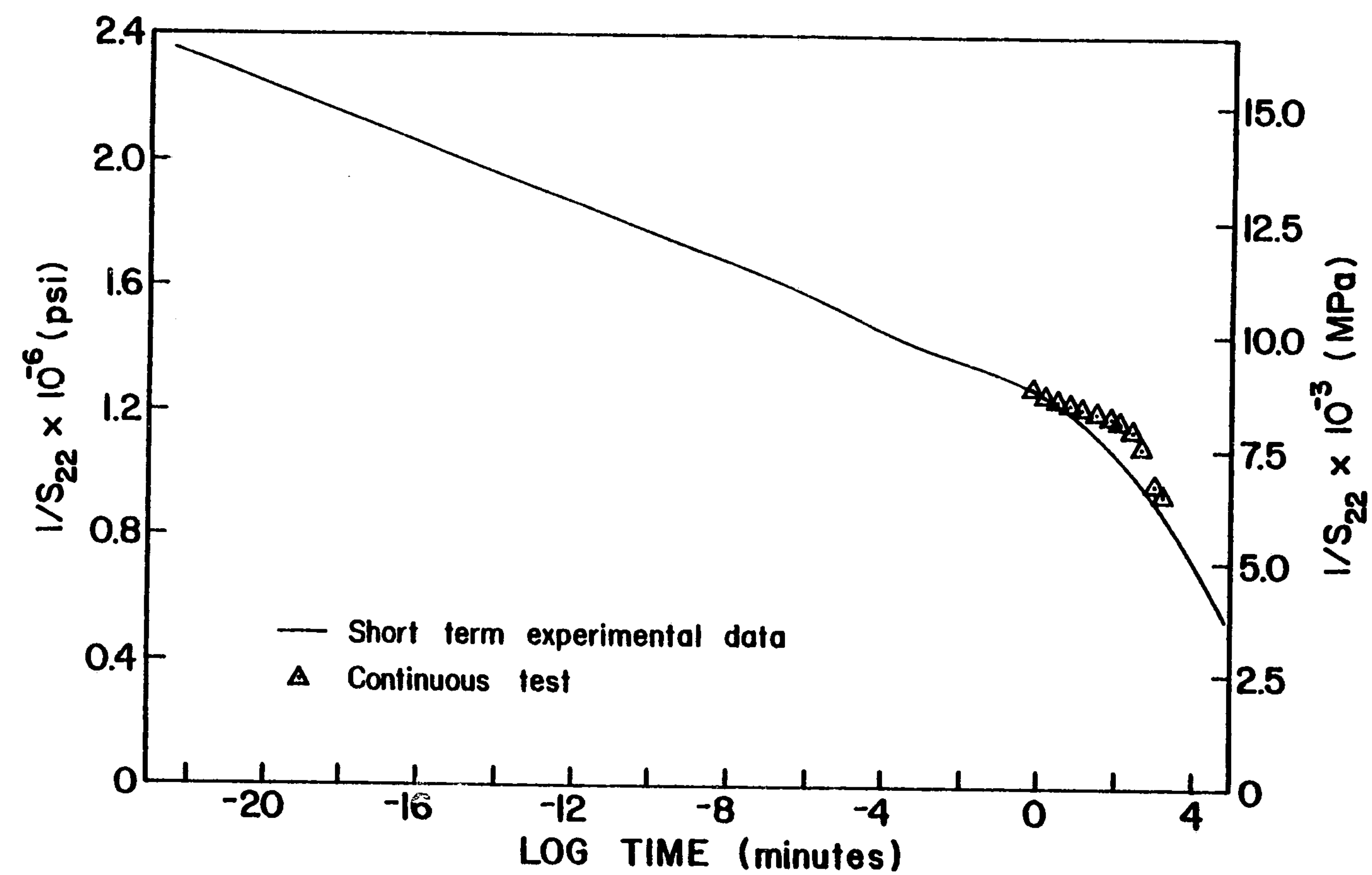

Fig. 3. Master Curve of the Reciprocal of Reduced Compliance of $[90°]_{8s}$ Laminate at 180°C

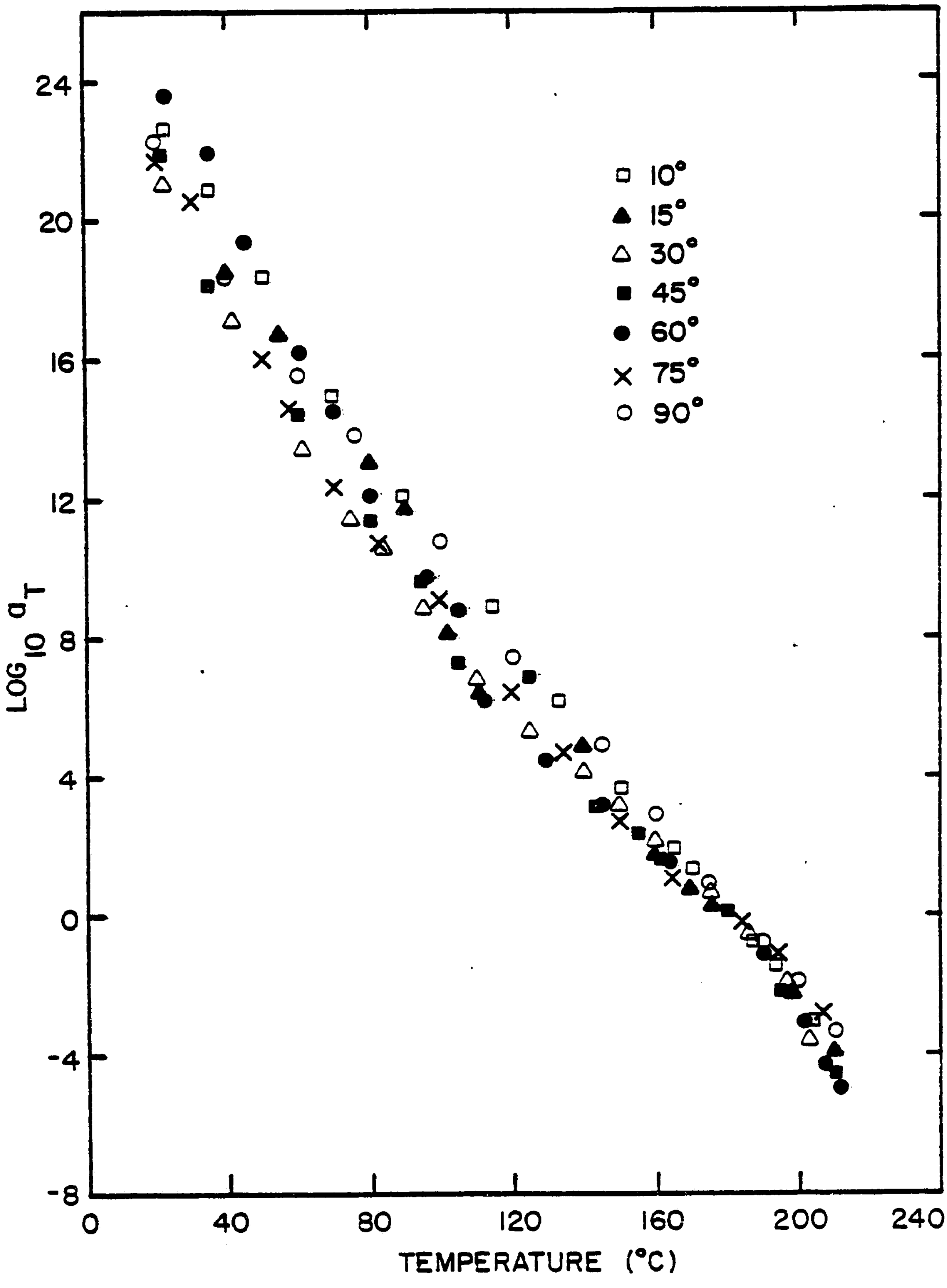

Fig. 4. Shift Factors Versus Temperature for Creep of Off-Axis Tensile Coupons (T300/934 Graphite/Epoxy)

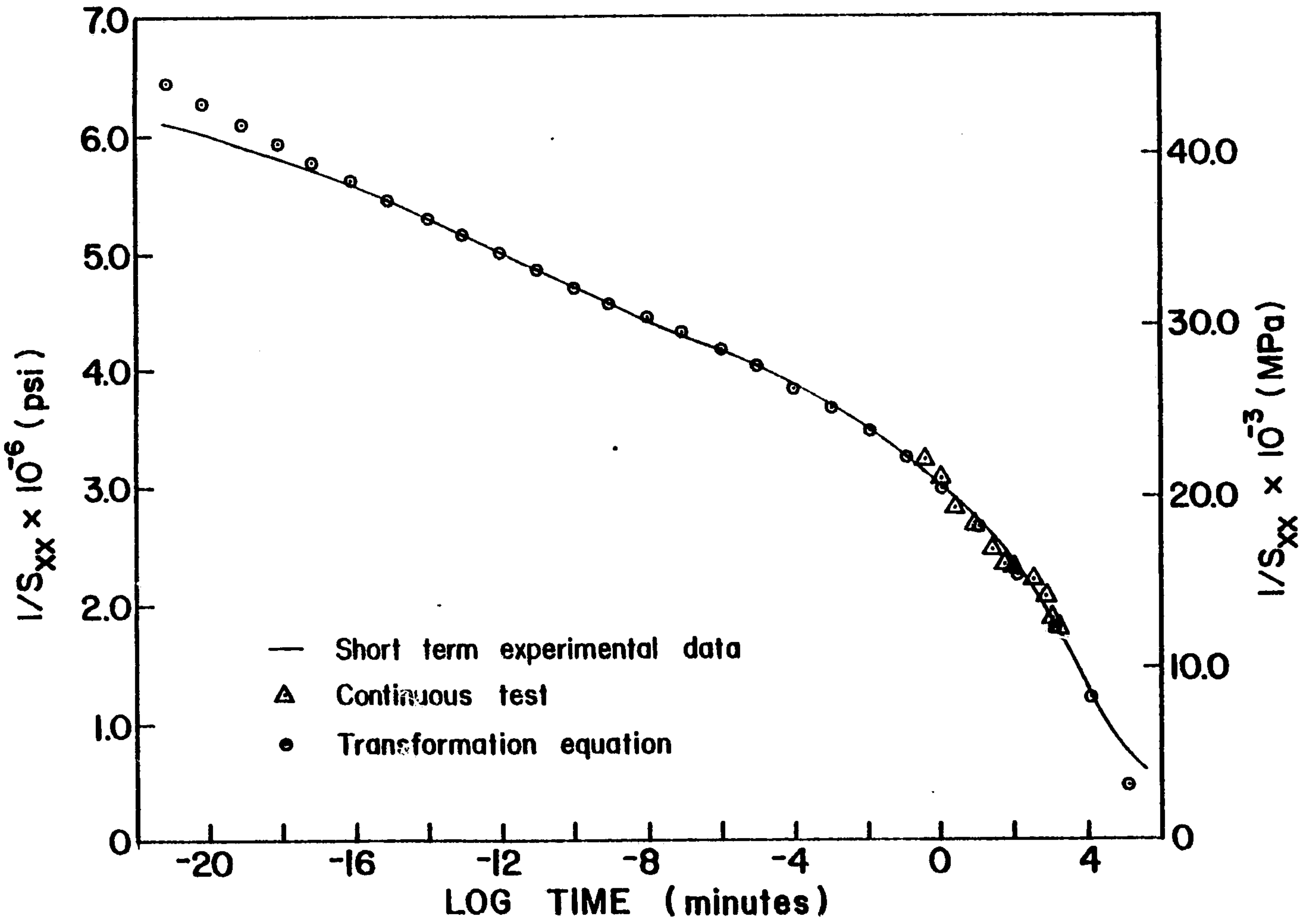

Fig. 5. Master Curve of the Reciprocal of Reduced Compliance, $1/S_{xx}$, of $[30°]_{8s}$ Laminate at 180°C

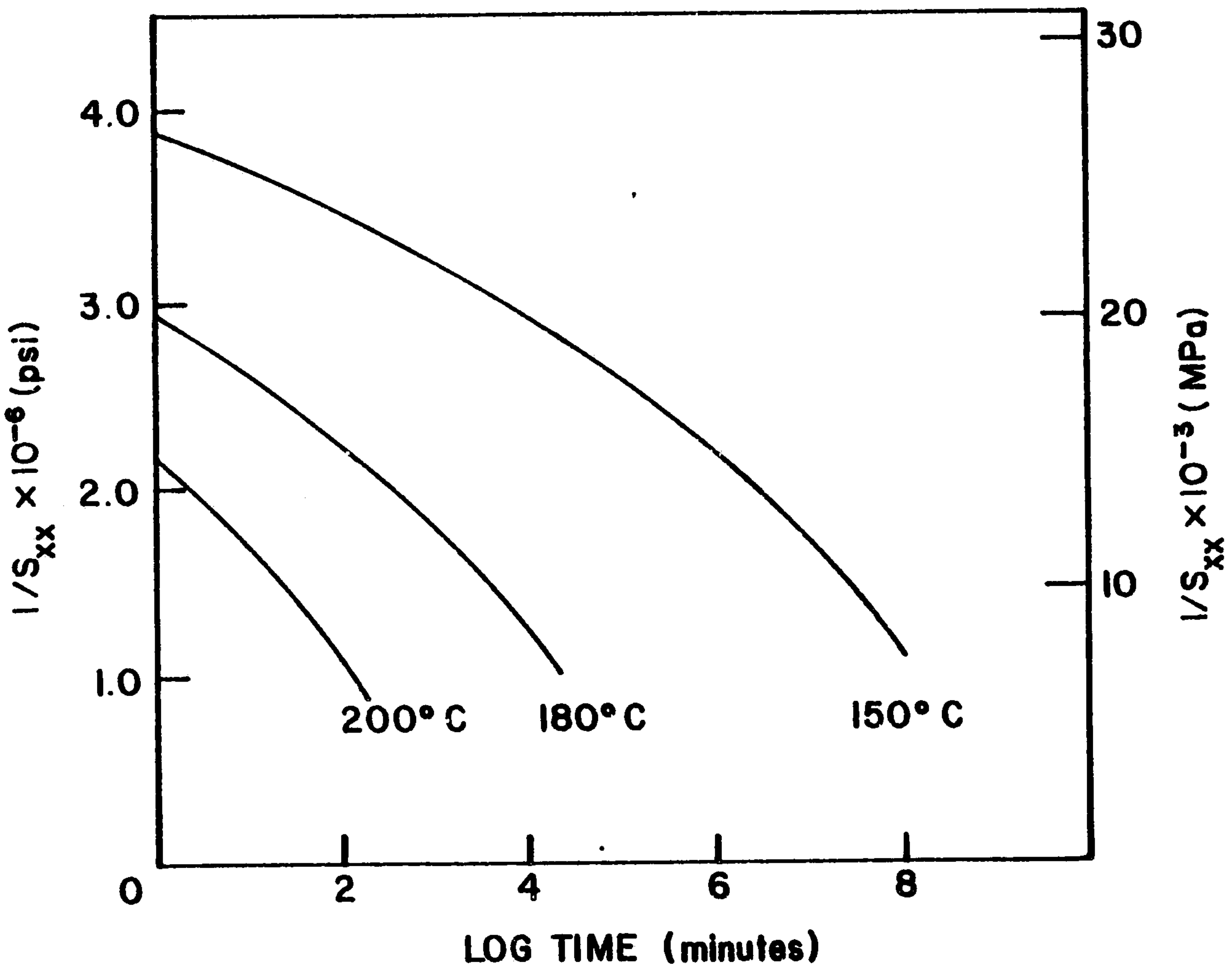

Fig. 6. Predicted Master Curves of the Reciprocal of Reduced Compliance, $1/S_{xx}$, of $[30°]_{8s}$ Laminate at Different Temperatures

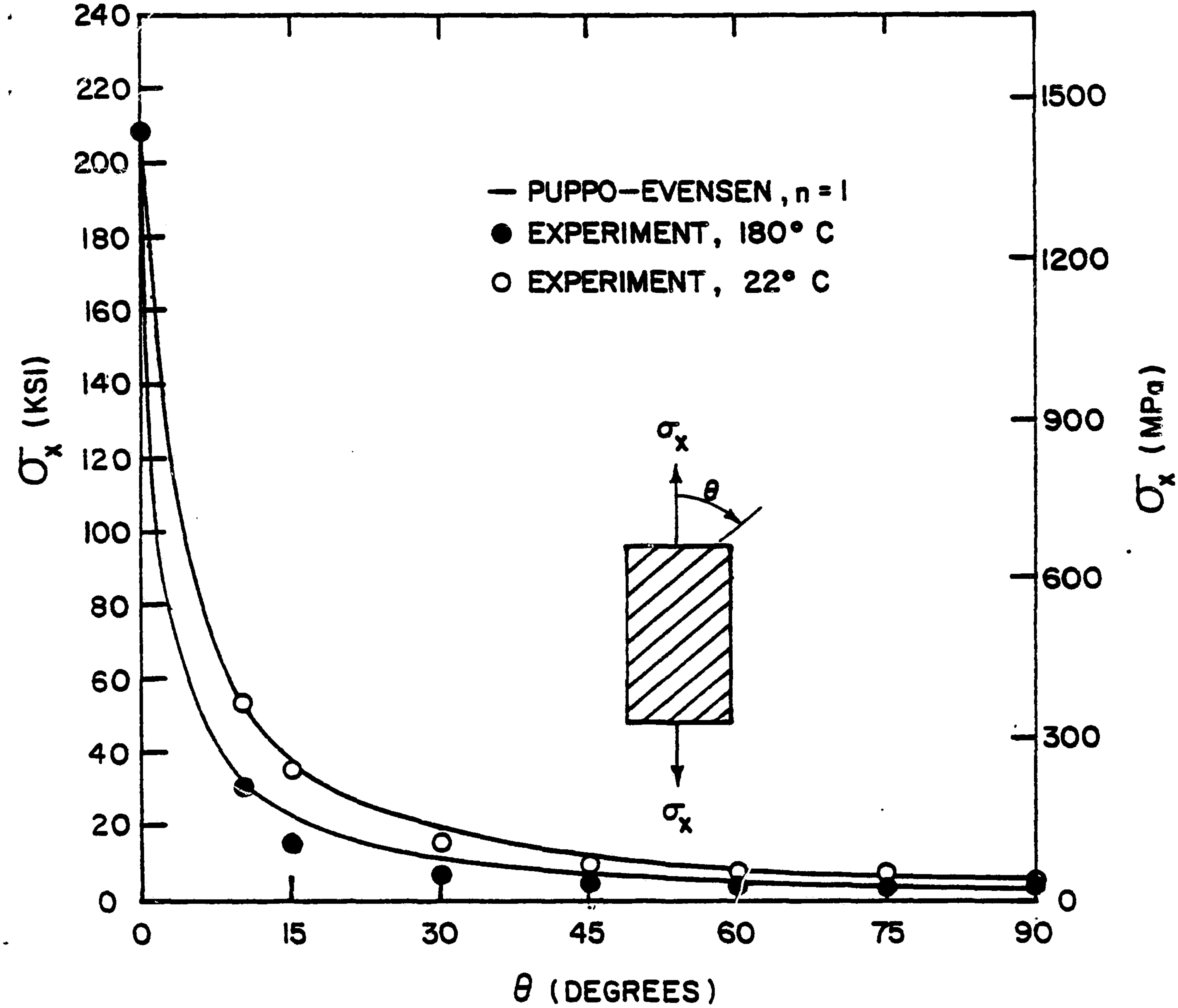

Fig. 7. Comparison of Experimental and Predicted Off-Axis Strengths (Ramp Loaded to Failure

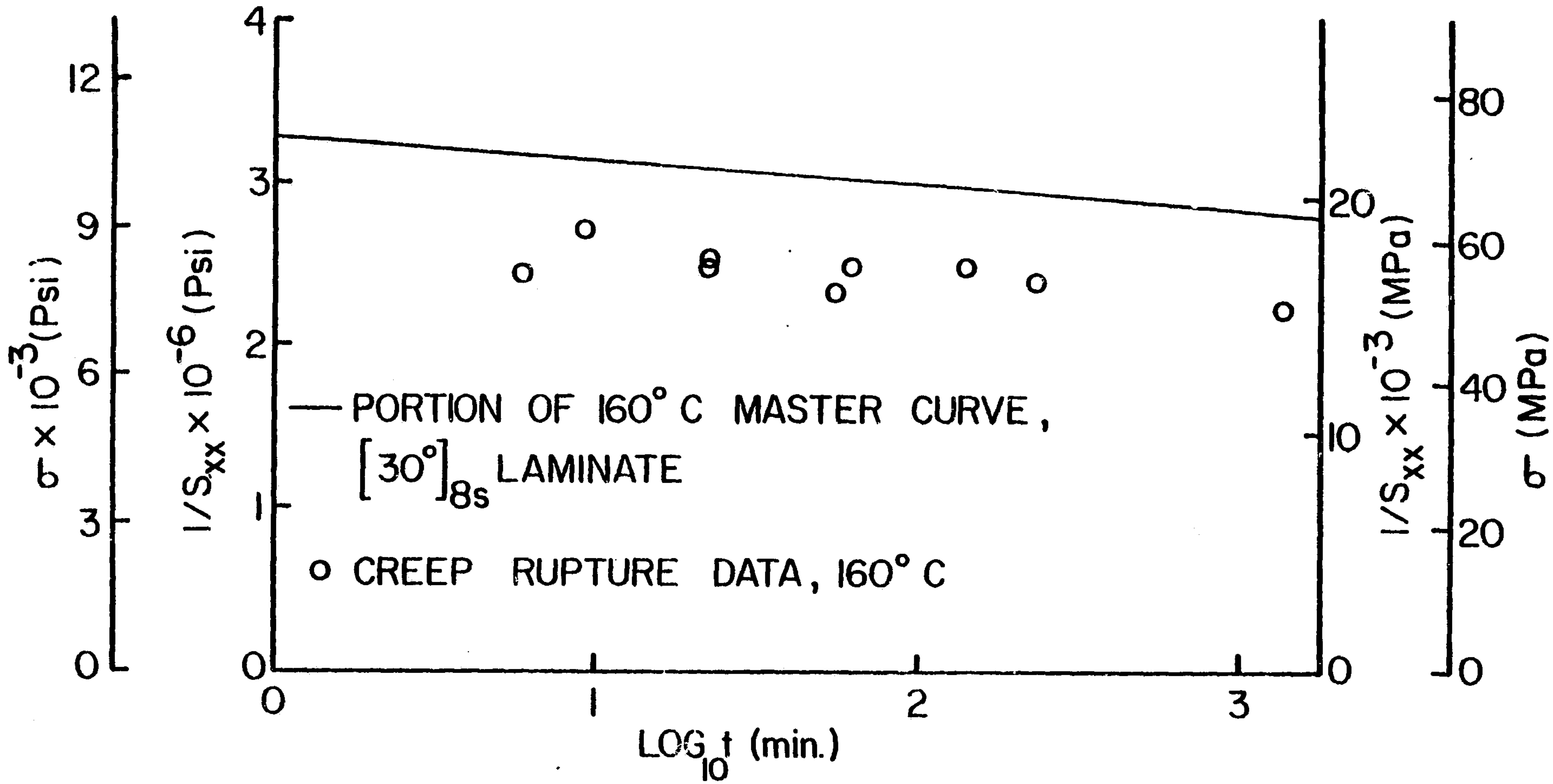

Fig. 8. Comparison of $[30°]_{8s}$ Creep-Rupture Predictions and Experimental Results

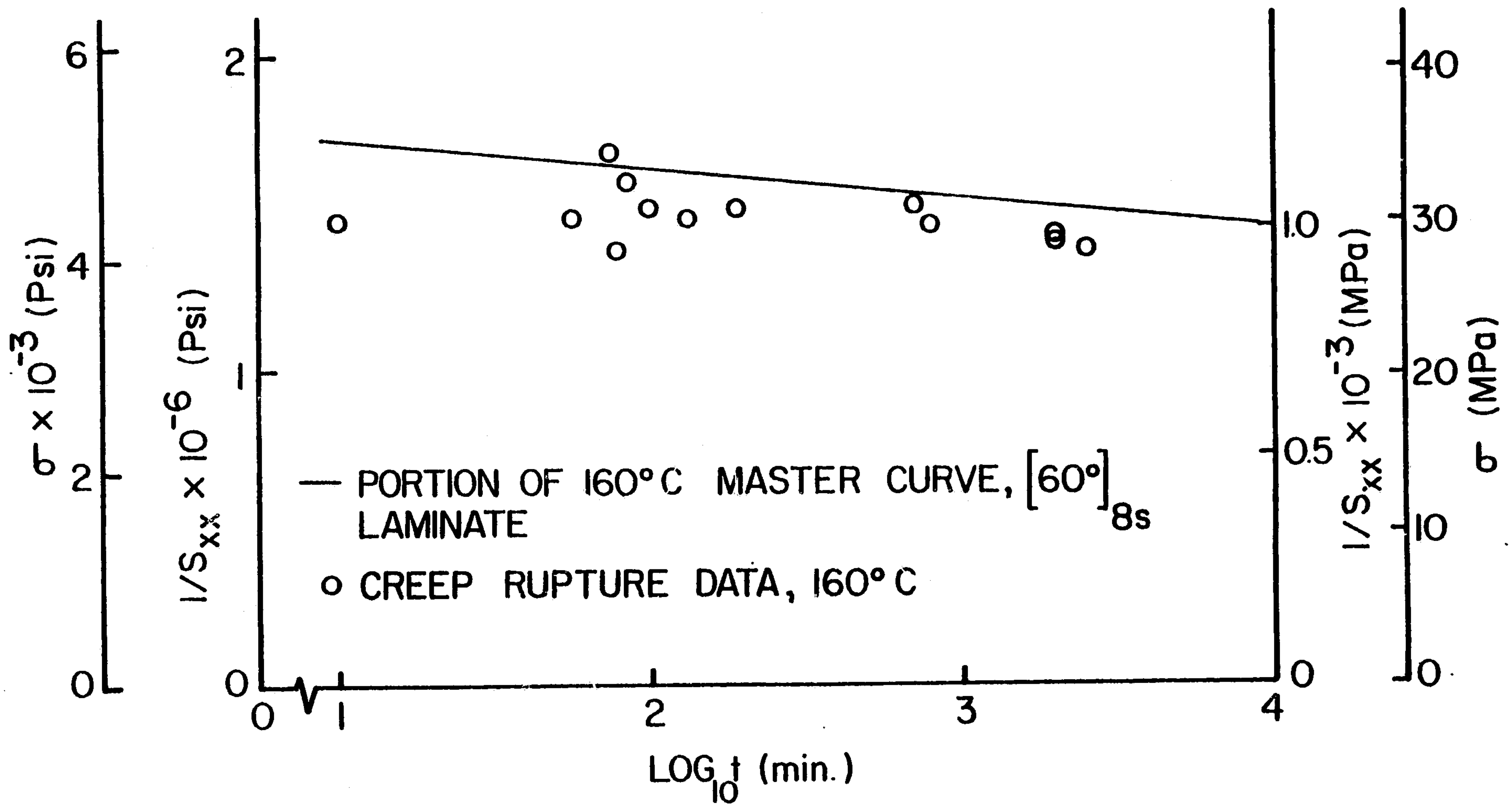

Fig. 9. Comparison of $[60°]_{8s}$ Creep-Rupture Predictions and Experimental Results

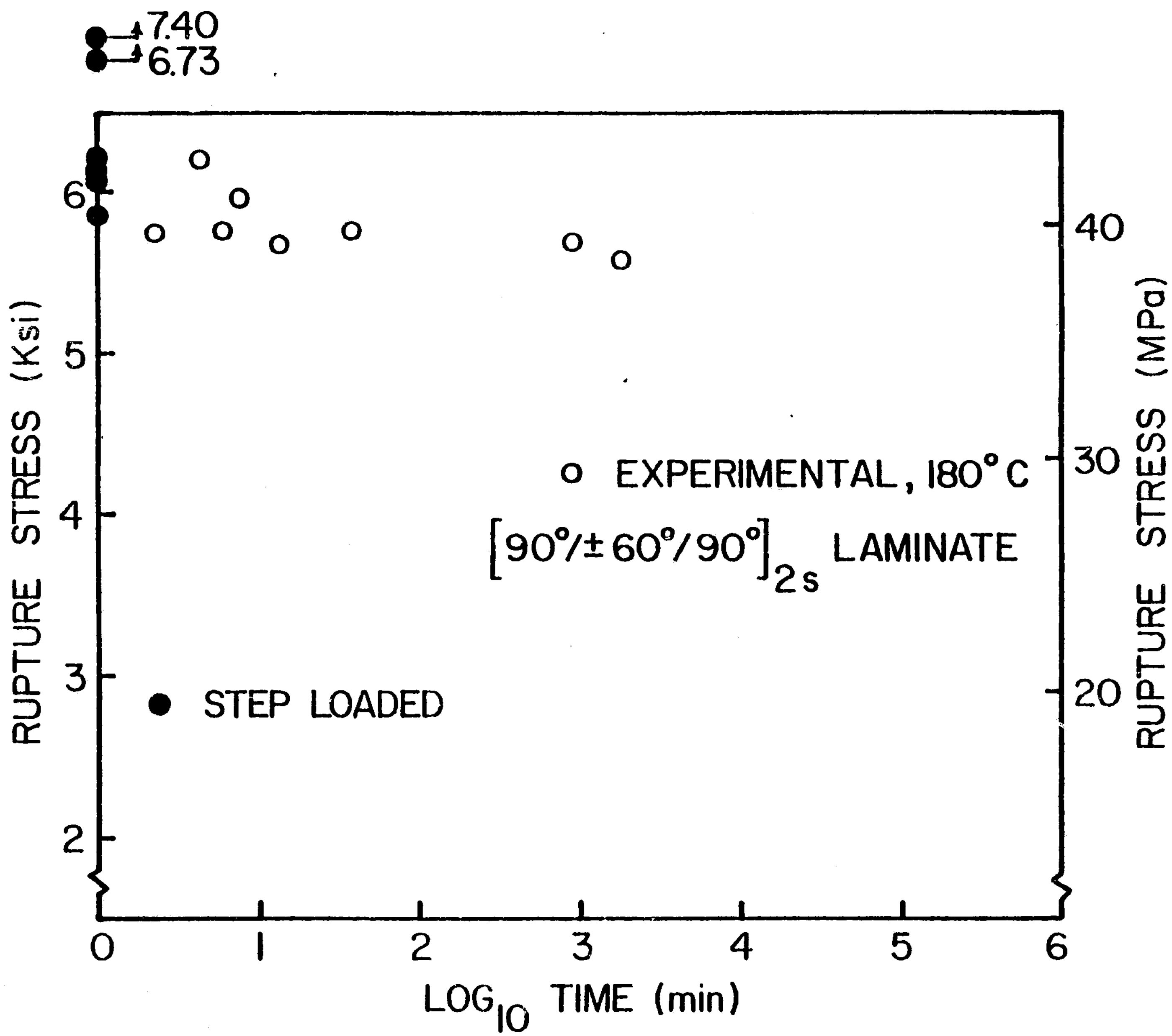

Fig. 10. Creep-Rupture of $[90°/\pm 60°/90°]_{2s}$ Laminate at 180°C (Solid Circles Represent Step, or Ramp Loaded Tests)

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